

Who is the Inflaton?*

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Abstract

In the context of the two-fluid model introduced to tame the trans-planckian problem of black hole physics, the inflaton field of the chaotic inflation scenario is identified with the fluctuation of the density of modes. Its mass comes about from the exchange of degrees of freedom between the two fluids.

Introduction

In addition to all else, the major scientific revolutions of the 20th century, quantum mechanics and relativity, have made it possible to envision cosmogenesis on a rational basis. Moreover, the theoretical approach that is envisioned has the potentiality (which has at present to some extent been realized), of making contact with present day cosmological observations.

The full awareness of this potentiality came in the late 70's and early 80's. It was first pointed out [1] that gravity together with the quantum theory of matter allowed for the creation of matter *ex nihilo*. At the same time it was shown that creation of matter at a constant rate gave rise to an exponential expansion of the scale factor [2], now called inflation and that this cured the perplexing problems of causality [2] and flatness [3] posed by

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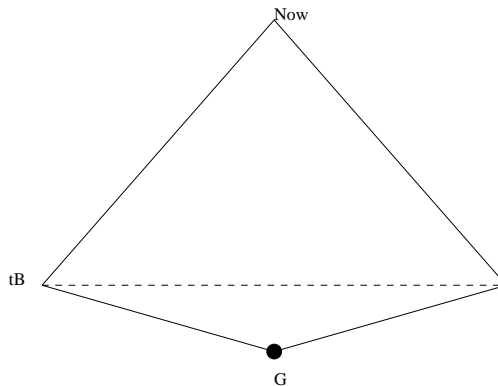


Figure 1: A schematic view of the causality problem

the Friedman Robertson Walker adiabatic expansion. A glance at Figure 1 is sufficient to give one a rough appreciation of the causality problem and how one envisions its solution in terms of creation *i.e.* cosmogenesis. Now one gathers information contained within the backward light cone as drawn. At big bang time (t_B), this backward extrapolation ceases to make sense, if the space-like surface at $t = t_B$ contains 1 degree of freedom per planckian cell. There must be at least 10^{90} such cells since this is the number of degrees of freedom present within the horizon now, and this number is conserved during the adiabatic expansion (to $\mathcal{O}(1)$). Though on the way from t_B to now there is some contact among the degrees of freedom due to scattering, this is far from enough to account for the observed homogeneity of the CMBR or galaxy distribution (see [4] chapter 8 for details). Therefore the homogeneity required at $t = t_B$ should result from a prior cause. It is postulated that there is a germ, G , from which energy is created and that the region, which contains this energy, expands exponentially. This will be realized in the time interval between G and t_B if the energy density remains approximately constant within the region where the energy is created. This is inflation.

An approach similar to that of [2] was also suggested during this early period which was based on vacuum energy in the form of the trace anomaly [5]. Whereas these early attempts were based essentially on production of kinetic energy, be it in the form of particles [2], black holes [3] or zero point energy [5], a new tactic was introduced in the early 80's which relied on potential energy. The first idea in this vein was latent heat released in a first

order phase transition [6]. It was postulated that the universe cooled down from a prior state of high temperature whereupon at some point the matter contained within would condense. But it was recognized at once [6] that this approach could not work. The condensed phase would be delivered in bubbles which would be swept out by the expansion too fast to allow for their coalescence. In addition I find that such a scenario would be epistemologically dissatisfying. If one is out to solve the causality problem, then one would hope that the cause in question is the cause of the universe i.e. one would like cosmogenesis and inflation to go together. To push the ultimate problem further backwards in time is, in a sense, to escape the problem. But this is merely my subjective opinion.

Fortunately, this approach could be modified through the invention of “slow roll” mechanisms [7, 8]. This removed the problem of non coalescence of bubbles since there would be time enough. Moreover in Linde’s hands [9] chaotic inflation came into being. We shall not here enter into details of how Linde envisages fluctuations within fluctuations, but simply give that part of the idea which we shall adopt in the foregoing. (We also refer the reader to [3] for further consideration of this question of fractalizing the fluctuation). The point of view we shall take here is that there is a state of rest in which there is no universe. But because of quantum mechanics the “stuff” in this space fluctuates. The stuff is complicated in its nature. Only at the long distance scale (and here we adopt the traditional point of view that the only fundamental scale is planckian) does usual field theory apply. The short distance scale is described by a “planckian soup”, the present great unknown of physics. It may involve higher dimensions and/or non-commutative geometry and/or strings and/or black hole fluctuations and/or... Whatever, we shall only suppose that it is described by a density or, if one wishes, a scale which is planckian. The abovementioned state of rest is interpreted variationally. The mean density in this state is postulated to be the state of minimum energy density in which there is no expansion of the scale factor in the metric that describes this state. We shall postulate that this space time is flat *i.e.* $\langle T_{\mu\nu} \rangle = 0$, $T_{\mu\nu}$ being the energy momentum tensor of everything.¹

This quiescent state of things is conceived as metastable. Fluctuations

¹François Englert has suggested to me that I could well let up on my stringent assumptions and introduce a small fundamental cosmological constant to describe this state. This would not do injustice to the sequel. For the novice I conform to what is most simple and most natural (perhaps ?).

that are small both in amplitude and extension will regress and leave no permanent effects. But now comes this wondrous conjunction of quantum mechanics and relativity.

In the hamiltonian formulation of general relativity, the total energy density of gravity + matter sums to zero.

Instrumental in the realization of this fact is that the kinetic energy carried by the motion of the scale factor, a , is negative (*i.e.* in the hamiltonian density there is a term in $(-H^2)$ where H is the Hubble constant: $H = (\dot{a}/a)$, where dot is derivative with respect to proper time). Thus the positive energy density of a fluctuation of matter density is necessarily accompanied by $H \neq 0$, so as to keep the energy density equal to zero. This constraint is strict; even in the future when fundamental theory will relegate the Einsteinian theory of gravity to successful long scale phenomenology it will probably survive. It is due to the invariance of the total action against reparametrization of the temporal coordinate and one would be loath to give up such a fundamental principle in whatever guise it will express itself in future theory.

It is herein that opens the possibility of permanent effects of a fluctuation. If this latter is large enough in amplitude (to allow for a systematic temporal development) and in extension (so as to render spatial gradients sufficiently small in energy as compared to the total energy of the fluctuation) then it will be seized upon by the scale factor and will expand exponentially immediately after its formation. After a while the fluctuation will nevertheless regress and one postulates its energy is converted to ordinary quanta whereupon the entropy so produced remains constant and FRW adiabatic expansion ensues.

At the present time, the formal development of the above scenario is executed in terms of a scalar field. All the aforementioned concepts fall neatly into this development and furthermore, detailed quantitative analysis has shown that it is possible to account for presently observed density fluctuations both of the anisotropy of the CMBR and the distribution of galaxies. For details see [4], chapter 8, and the lectures of Lazarides at this summer school and workshop at Corfu 2001.

It is my purpose here to dwell on the possible nature of this fundamental fluctuation, often called the "inflaton" field albeit in highly speculative fashion. Who is he, this inflaton ?

My inspiration has been in great measure drawn from the experience that has been garnered from the theory of black hole physics over the past decades and which finds its expression, in the 2-fluid phenomenology that has been developed in recent years [10].

The Cosmological Fluid *vs* its Material Counterpart

The theory of Hawking evaporation [11] from black holes, (and we take as the simplest example s-wave emission from Schwarzschild black holes) encounters the transplanckian problem. In the original version of the theory, Hawking studied free field propagation in the background Schwarzschild metric. He showed that a vacuum fluctuation in the vicinity of the horizon, as it propagates towards spatial infinity, is possessed of an amplitude which in part becomes that of a physical on massshell quantum due to the changing metric it experiences in its voyage. The distribution of these quanta is thermal, at least for frequencies of the order of or larger than the inverse horizon distance $\sim m_{pl}^2/M$, where M is the mass of the black hole. In the derivation of this remarkable phenomenon one appeals to configurations of fields which are localized to within fantastically small distances of the horizon $\Delta r \sim M e^{-\alpha M}$ (where $\alpha = \mathcal{O}(1)$). Here and from now on we work in planckian units $m_{pl} = 1$. Correspondingly the energies involved in such configurations are $\sim M^{-1} e^{\alpha M}$ and this, for a macroscopic black hole where $M \sim 10^{60}$, is ridiculously large.

Since gravitational interaction grows with the product of the energies of the interacting entities it is seen that the modes which contribute to Hawking radiation interact extremely strongly in the regions from whence they come in order to deliver their asymptotic flux. Therefore the picture of free mode propagation breaks down. Unruh [12] has shown nevertheless that this does not kill the effect. All that one requires is a condition that had been previously proposed by Jacobson [13], to wit : at some finite distance from the horizon one still has vacuum conditions. A likely distance is $\mathcal{O}(1)$ *i.e.* m_{pl}^{-1} . Unruh showed that if one tinkered with the dispersion relation, $\omega(k)$, in a manner similar to that of phonons in fluids where ω cuts off at $k = (\text{interparticle distance})^{-1}$, then Jacobson's condition is met *i.e.* Hawking radiation is robust. Unruh's analysis was numerical, but it has also been demonstrated analytically [14, 15].

Since then, other models have been proposed, one based on a deformed commutator [16] and another which takes into account scattering between incoming and outgoing modes [17]. In these latter cases backward extrapolation of the emitted Hawking quantum results in its disappearance once it enters into a region which is localized around the horizon, which one supposes is given on the planckian scale (at least in [16]; in [17] this specification is more complicated). In both cases Hawking steady state radiation in asymptotia is maintained whereupon the picture emerges that the quanta boil off

from a horizon region, *i.e.* there is some kind of planckian soup which serves as a reservoir of “cisplanckian” quanta.

All of this to motivate a two-fluid picture of space-time and the matter in it, wherein the large length scale physics is described by conventional field theory, modes (and their interactions) which propagate in a fluid which describes the physics at small length scale. The scale at which the dichotomy takes place is the cut-off of modes, hence proportional to $n^{-\frac{1}{3}}$ where n is a parameter which describes the density of modes. We expect $\langle n \rangle = \mathcal{O}(m_{pl}^3)$.

Our experience in black hole physics has emboldened us to take this picture seriously. Hawking radiation is, in no small measure, as solid as thermodynamics (for the eternal black hole this statement is based on the periodic structure of Green’s functions in imaginary time in Schwarzschild coordinates in the region of space-time where this description is appropriate. It is also a necessary concomitant to the elimination of unphysical singularities in $T_{\mu\nu}$ in the region of the horizon). We know that the mode picture must fail once we reach planckian scales owing to mode-mode interactions so that beyond that scale, strong interaction physics take over. And this we do not how to formulate. But the one acid test where quantum field theory is confronted with strong effects of gravity, the black hole, has taught us that we can account correctly for a phenomenon which is solidly established, Hawking emission, using this cut-off low momentum sector whilst remaining non committal concerning the nature of the planckian soup. And further from [16] and [17], this soup serves as reservoir for the low momentum modes.

What does this have to do about the inflaton and the primordial cosmogonic germ? The answer lies in quantum mechanics. The collective variable, n , appears in our description of the wave function of everything. Therefore it fluctuates. Moreover it fluctuates locally. It is a field $n = n(x, t)$. Our proposition is that at least one piece of the physics that is described phenomenologically by an inflaton field is the fluctuation of n . There may be more to the inflaton than n alone, due to the dynamics of matter. For example supersymmetry and its breaking may have important physical repercussions on how $T_{\mu\nu}$ fluctuates. But, given our present appreciation of gravity in its quantum context, fluctuations of n are inevitable. Whether this is ultimately determinant, (*i.e.* whether the fluctuation of n is the germ) is a quantitative question which requires further research. In the foregoing paragraphs I shall simply indicate that the fluctuation of n has the qualitative attributes that one attributes to the inflaton field. Hopefully more quantitative support (or

negation) will emerge in subsequent work.

One very important question is that of the cosmological constant Λ . I am assuming $\Lambda = 0$ in the initial quiescent universeless state (at least in the region of space-time that holds our universe). I am therefore waiving the interesting problem posed by the existence of Λ now, which appears to the same order of magnitude of the present energy density $\sim 10^{-122} m_{pl}^4$. This seems more like a tuning problem than the fundamental issue we are facing here where by all rights one might have expected $\Lambda \sim m_{pl}^4$.

The answer to why $\Lambda = 0$ at the beginning may be presumed to be hidden in the variational principle which fixes $\langle n \rangle$ *i.e.* in the quiescent state one has $\partial \langle \epsilon \rangle / \partial n \big|_{n=\langle n \rangle} = 0$ where $\langle \epsilon \rangle$ the mean energy density. One must find out why $\langle \epsilon(n = \langle n \rangle) \rangle = 0$.

The question is nigh to impossible to answer. This is because the energy of space-time in this 2 fluid picture takes the form

$$\epsilon(n) = \epsilon_{mode}(n) + \epsilon_{soup}(n) + (\text{interactions between soup and modes}) \quad (1)$$

We only know something about $\epsilon_{mode}(n)$ *e.g.* the zero point contribution is $\sim n^{\frac{4}{3}}$. Of all the rest we are ignorant.

There are two points of view which one can adopt in setting $\Lambda = 0$. One is the time honored procedure of blind subtraction. This can be couched in somewhat more elegant terms as a sort of Aristotelian principle of absolute rest, to wit: gravity does not respond to the configuration of fields which is at the rock bottom of $\epsilon(n)$. It only responds to the fluctuations *i.e.* to $\tilde{\epsilon}(n) = \epsilon(n) - \epsilon(\langle n \rangle)$ where $\epsilon(\langle n \rangle)$ is the value of $\epsilon(n)$ at its minimum.

The alternative possibility is that $\Lambda = 0$ is a principle, say as fundamental as the principle of equivalence. This would fix $\epsilon(\langle n \rangle) = 0$. The implication is that there is a balancing out of parameters which appear in the various terms of (1), which arranges things just so. (Using foam models it is easy to make such constructions, but they are on no more nor less fundamental grounds than the more usual *ad hoc* subtraction).

Be that as it may, an expansion about $\langle n \rangle$ leads to

$$\tilde{\epsilon}(n) \approx \frac{1}{2} B (\delta n)^2 \quad (2)$$

where $\delta n = n - \langle n \rangle$; $B = \partial^2 \epsilon / \partial n^2 \big|_{n=\langle n \rangle}$

An important point is to realize the difference in consequences of (2) when one compares the cosmological fluid to a stable material fluid where (2) would

also apply (say to a superfluid at zero temperature). The difference lies in the conservation of the elements (atoms) which make up the latter and their non conservation in the former. (For example, in the naive model of foam made up of instantons, in virtue of the very word, these entities come and go).

At this point, it is meet to set out an important caveat. It has been argued in [10] that $\Lambda = 0$ in virtue of stability. This argument is insufficient because it is based on conservation of the number of atoms. It is worth setting out the argument since it then allows one to appreciate why density fluctuations are massless in the case of material liquids, but massy in the cosmological case.

Consider a superfluid at zero temperature. It is stable *i.e.*

$$-p = (\partial E / \partial V)_{N, T=0} = 0 \quad (3)$$

An observer inside the fluid uses the grand ensemble to describe his physics *i.e.* within the volume, V , which is within his scope of observation, particles come and go and this is accounted for by making use of the energy in V which we will denote by $\tilde{E}(V)$

$$\tilde{E}(V) = E(V) - \mu \langle N \rangle \quad (4)$$

where $\langle N \rangle$ is the average value of N in V and μ = chemical potential ; $\mu = (\partial G / \partial N)_{p, T}$ and at $T = 0$, $G = E + pV$. Also since $p = 0$ in virtue of stability we have $G = E$, whence

$$\tilde{\epsilon} = \tilde{E}/V = \epsilon - \mu n = 0 \quad (5)$$

The conditions $\tilde{\epsilon} = p = 0$ are translated into zero cosmological constant.

The argument is not applicable to the cosmological fluid since N is not conserved whence $\partial / \partial V|_N$ is not a physical variation. Rather $p = -dE/dV$ at $T = 0$ *i.e.* as V varies, N can vary with it to keep the density n (whose average is $\langle N \rangle / V$) at its optimal value. In other words, as V varies particles can pop in and out of the vacuum so as to keep $\langle N \rangle / V$ fixed. Therefore stability does not imply $p = 0$.

The true variational principle in this case is

$$\mu = (\partial E / \partial N)_V = 0 \quad (6)$$

One is generally led to believe that $\mu = 0$ when number is not conserved is a negative statement. If you don't need it then it is zero. In the present case,

this is also true, but it is a more powerful statement than usual in that (6) fixes the density to be optimal. It also implies $\partial\epsilon/\partial n|_{n=\langle n \rangle} = 0$. And this is a far cry from $\epsilon(n = \langle n \rangle) = 0$.

What (6) does imply is that the mean energy of the ground state of the cosmological fluid is delivered in the form of a cosmological constant. Indeed

$$\mu = \langle \epsilon \rangle + p = 0 \quad (7)$$

means $p = -\langle \epsilon \rangle$. In general relativity this means $\langle T_{\mu\nu} \rangle = \Lambda g_{\mu\nu}$ where in this case $g_{\mu\nu}$ is flat. But, to repeat, one must further to prove $\Lambda = 0$, and this is a great problem which continues to be vexing.

Let us now continue with (2) and show that it invites the proposition that δn is a massy scalar field which describes density fluctuations in the cosmological fluid, hence having the property that one associates with the inflaton. The physics, once more, is brought out by comparison with the material fluid.

Because N is conserved in the material fluid density fluctuations have no zero Fourier component. Thus there must be no physical manifestation of the $k = 0$ component of $\delta n(r, t)$, whence $\omega(k = 0) = 0$. If this is the terminal point of a continuous spectrum than the mass of the field $\delta n(r, t)$ is zero. The way this is realized is to compute the pressure gradient that is induced by a density gradient $\nabla p = B \nabla n$. This pressure gradient causes acceleration of the fluid element (*i.e.* temporal variations in the fluid current j). Using the equation of continuity, $\partial n / \partial t + \nabla \cdot j = 0$, then straightforwardly one produces the wave equation for sound with $\omega^2(k) \sim Bk^2$.

What is important is that all the energy of a fluctuation is in the spatial gradients plus the acceleration that these induce in the form of kinetic energy *i.e.* $E \sim (\nabla n)^2 + \frac{1}{c^2} \dot{n}^2$ for small fluctuations where c is the velocity of sound, $c \sim \sqrt{B/m}$.

Now consider the cosmological fluid. Here the $k = 0$ component does exist. Thus one can have a fluctuation profile which looks like Figure 2. This is the form one is talking about in inflation and indeed it is how one thinks about the germ. And there is no reason in the world why such fluctuations of n should not exist. In addition to the usual energy lodged in gradient terms as in regions A , there is present a flat region B where the gradient vanishes or is small. Nevertheless its energy exists. It is pulled out of the quiescent configuration because absolute quiescence is not a quantum concept; $[\epsilon(n) - \epsilon(\langle n \rangle)] \neq 0$ can come about by changing the density of modes

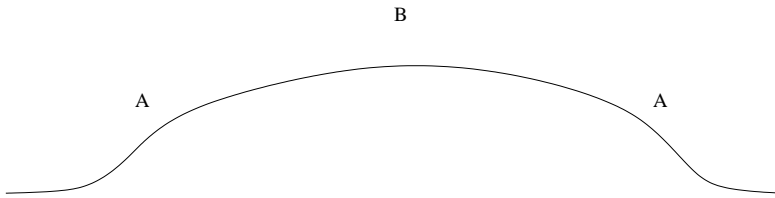


Figure 2:

and or soup in a region without recourse to $\nabla n \neq 0$ in that region. Thus the term $\frac{1}{2}B(\delta n)^2$ can and does contribute to $\frac{1}{2}m^2\varphi^2$ where φ and m are a scalar field (the inflaton) and its mass.

Of course gradients will exist in any finite size fluctuation and they will carry energy. On grounds of covariance their action will be proportional to $g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi$. To calculate the relative weights of these kinetic terms as compared to the potential term is a dynamical problem which must be addressed.

To assert that the inflaton is δn is premature. Various models must be tested to see if the parameters one comes by are acceptable. But it is fairly clear that whatever the inflaton turns out to be, the fluctuation of the fundamental “stuff” which we now contemplate as the point of departure for the formulation of quantum gravity must play some rôle. It may be one element of a highly complex process involving any one of the number of candidates presently considered at the foundation of matter and gravity, or for all we know it may be the whole story.

We close this rather unsatisfactory speculative discourse with some additional remarks.

1) Since n is proportional to the density of modes (essentially $n^{\frac{1}{3}}$ is the cut-off), fluctuations of n will cause not only fluctuations of mode density. Some of these fluctuations will end up as those which one calls upon to account for present fluctuations of the CMBR and structure. Another part will cause the production of quanta due to the nonadiabatic variation ($\delta\dot{n} \neq 0$). Since δn regresses, one obtains particle production. This is in analogy to production of phonons induced by the finite rate of change of density in a solid. Once more details are required to see if this is the source of the entropy we observe.

2) One must not lose sight of alternatives to the inflaton scenario. Hawking has investigated black hole pair fluctuations in vacuum. It is not impos-

sible that there are rare abundant coherent fluctuations which will be seized upon by the scale factor and which will inflate just as the fluctuation of φ inflates. This is but one example. To be sure the scenario of chaotic inflation has to some extent “won its spurs”. But fundamental cosmology is essentially speculative in character. Any argument that works is an argument of sufficiency, not of necessity. So I conclude, it is too easy to be complacent. We are probably going to meet no end of surprises before we can reach some consensus of opinion on just what it is that is responsible for the birth of our universe.

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1 Added note

After the completion of this text, I analyzed somewhat further the potential energy of the fluctuations of the mode density by separating it into two parts:

1. the “acoustic” contribution generated by pressure gradients wherein total number is conserved,
2. a source term occasioned by exchange of a degree of freedom between the “planckian soup” and the “vapor of modes”.

When the soup is modeled by a collection of black holes (or, in general, entities with horizons), then the source generates an inflaton mass of order of magnitude

$$\mu^2 \approx \exp(-|\Delta S|) m_{Pl}^2$$

where ΔS is the entropy change of the black hole that is induced by the exchange. For Schwarzschild black holes this is given by $\Delta S = 8\pi M \bar{\omega}$, M = mass of the black hole, $\bar{\omega}$ = mean energy of modes. One expects both M and $\bar{\omega}$ to be $\mathcal{O}(m_{pl})$ whereupon one finds $\mu = \mathcal{O}(10^{-5})m_{pl}$. This is the order of magnitude required by the analysis of present day cosmic fluctuations. N.B.: The above estimate is very crude and can easily change by several orders of magnitude due to its sensitivity on M .